

Modeling the Impact of Supply Chain Resilience Configurations on Operational Performance: A System Dynamics Approach

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Abstract: In response to the current global unrest, this study proposes a new system dynamics simulation model to capture the effects of multiple configurations of supply chain resilience (SCRES) on a firm's operational performance. Instead of using a static, siloed approach to the analysis, this study models system resilience as the dynamic interplay of a system of interconnected building capacities for system flexibility, redundancy, agility, and collaboration and agility. The simulation attempts to model important feedback loops and non-linear interactions associated with a multi-echelon supply chain and recurring external shocks, such as demand shocks or supply interruptions. The operational performance of the supply chain is modeled as a weighted index of costs, service level, and recovery time. The simulation model is informed by data obtained from a recent manufacturing case study and demonstrates that the best operational performance of an SCRES system is not obtained by maximizing one building capability of the system. Rather, the optimal performance is spirited by synergistic configurations of several system-building capacities. The best collaborative long-term performance is obtained by a balanced investment in agility and collaboration to the exclusion of excess reliance on system building redundancy, which stabilizes the system at a very high operational price. The model also identifies SCRES as a non-linear system of collaborative trade, demonstrating that strategic collaboration with critical supply chain partners forms a positive feedback cycle that reduces system building costs of inventory buffers by promoting overall system SCRES. This research is a contribution to operations management theory by offering a comprehensive and dynamic perspective to understand SCRES as a configurational system as opposed to a collection of distinct practices. The outcomes of this research can serve as practical guidelines for managers on how to best use their scarce resources by suggesting a portfolio approach that focuses on adaptive capabilities rather than static redundancies for building a resilient operation.

Keywords: Supply Chain Resilience, Operational Performance, System Dynamics, Simulation Modeling, Resilience Configurations, Disruption Management, Multi-Echelon Supply Chain

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1. Introduction

According to [1], global supply chains are characteristically volatile global supply chains. In the past decade, businesses have faced significant challenges such as trade wars, the global COVID-19 pandemic, geopolitics, climate change, and cyberattacks. These challenges emphasize how vulnerable supply chains are when they are designed for efficiency over adaptability, as discussed in [3]. As discussed in [4], businesses seeking competitive advantage through operational efficiency are integrating global value chains at the expense of slack, thereby losing flexibility. This means that any one of their supply chain nodes is able to

send a big operational shock to the system, resulting in costly operational interruptions anywhere in their supply chain. This has resulted in a big shift of focus within supply chain management and called for new strategies in supply chain management resilience ([The exact reference for the SCRES page 155 goes here because you mention SCRES has a big shift in focus in this new reality]. SCRES is about gaining and maintaining a competitive advantage through operational continuity, disruption, and therefore operational flexibility. [5]

1.1 Problem Definition: The Configuration Challenge

Difficulty remains amongst academics and practitioners alike on how to arrange SCRES competences resourcefully (6). SCRES is not a simple construct but a compound construct consisting of core interconnected competences of flexibility, redundancy, agility, and cooperation/ collaboration. Managers encounter a difficult problem of optimal resource allocation (7). A manager must decide whether to put resources into inventory buffers (redundancy), flexible manufacturing & sourcing (flexibility), advanced analytic tools for better visibility (agility), or into strengthening partner networks (collaboration). The key problem is that these capabilities do not function alone. Instead, they are synergized in non-linear and even counterintuitive manners (8). For example, one might improve one's redundancy and preparedness, but lose efficiency, and then lose competitive advantage in the long run (9). On the opposite end, depending on agility alone might not be enough to weather a long-term severe disruption. Hence, the main problem of the research is to clarify the complex intertwining of these trade-offs on the different combinations of these dimensions of resilience and the impact of this combination on the firm's operational performance as a whole (10).

1.2 Theoretical Foundation: A Capabilities-Based View of Resilience

The foundation of this research focuses on the theory of dynamic capabilities of the firm and the resource-based view (RBV) within the context of the supply chain [11]. Such a perspective, within the subject of the supply chain, defines a resilient supply chain as one that, in addition to having certain dynamic capabilities to sense, forecast, and respond to disruptions, resourcefully restructures itself to retain its competitive standing [12]. From the literature, we highlight four key capabilities of a supply chain resilient to disruptions:

- **Redundancy:** The strategic holding of buffer resources (e.g., safety stock, backup capacity, multiple suppliers) to absorb disruptions [13].
- **Flexibility:** The ability to adapt processes, such as switching production lines, rerouting shipments, or qualifying alternative suppliers [14].

- **Agility:** The capacity to respond quickly to changes, enabled by real-time visibility, information sharing, and rapid decision-making [15].
- **Collaboration:** The strength of partnerships and the willingness to work jointly with supply chain partners on planning, risk sharing, and problem-solving. The theoretical gap lies in the lack of a holistic understanding of how these capabilities configure—complement, substitute, or synergize—to create a resilient whole that is greater than the sum of its parts [16].

1.3 Limitations of Existing Methodologies

Research questions related to SCRES cannot be appropriately addressed by employing traditional empirical techniques (case studies, surveys, linear regression), which is why these methodologies have been criticized. While these methodologies do have their merits in terms of variable selection and correlation identification, a few of their downsides include their static (quotation) perspective and time insensitivity, which means they do not capture the relative evolution over time of a disruption and the response to it. The modeling of the intricate feedback loops in supply chains is another pertinent drawback, e.g., the delays in one part of the chain leading to shortages in another part, prompting panic ordering (i.e., bullwhip effect) and aggravating the underlying issue. The failure to capture trade-offs of a situation (e.g., at what point the costs of added redundancy are not beneficial) is perhaps the most important reason. Hence, a methodology that endogenously represents the structure, interdependencies, and time-delayed feedback processes of a complex supply chain system is required.

1.4 The Proposed Approach: System Dynamics Simulation

To address these gaps, this research adopts **System Dynamics (SD)** simulation modeling. SD is a computational methodology specifically designed for studying the behavior of complex systems over time. It is uniquely suited for this research as it allows for:

1. The explicit mapping of a multi-echelon supply chain structure, including material flows, information flows, and decision-making rules.
 2. The formal representation of the four resilience capabilities (redundancy, flexibility, agility, and collaboration) as parameters within the model's structure.
 3. The simulation of various disruption scenarios (e.g., supplier failure, demand spikes) to stress-test the system.
 4. The analysis of the dynamic impact of different resilience configurations on key performance indicators (KPIs) like cost, service level, and recovery time.
- By using SD, we can move beyond correlation to conduct virtual experiments,

observing how the system behaves under different configurations and disruption scenarios that would be too costly or risky to test in the real world.

1.5 Research Objectives and Contributions

The primary objective of this study is to **model, simulate, and analyze the impact of different supply chain resilience configurations on operational performance using a system dynamics approach**. This overarching goal is broken down into several specific aims:

1. To develop a robust, validated SD model of a multi-echelon supply chain that incorporates the key elements of resilience.
2. To define and operationalize specific metrics for redundancy, flexibility, agility, and collaboration within the simulation environment.
3. To simulate the impact of various disruption events on operational performance under different pre-defined resilience configurations.
4. To identify which configurations of capabilities are most effective for maintaining performance across different disruption types and severities, and to elucidate the synergies and trade-offs between them.
5. This research contributes to theory by providing a dynamic, holistic framework that captures the interdependencies between resilience capabilities, addressing a significant gap in the literature. For practice, it offers managers a powerful "what-if" simulation tool to support strategic decision-making, allowing them to visualize the likely outcomes of different investment choices and ultimately build more robust and cost-effective supply chains.

Table 1: Supply Chain Resilience Configuration Variables

Variable	Description	Units	Impact on Performance	Modeling Approach
Lead Time	Time taken for goods to move from suppliers to customers	Days	Longer lead time reduces resilience	System Dynamics Stock-Flow Model
Inventory Buffer Size	Amount of inventory kept as a buffer for unexpected demand fluctuations	Units	Larger buffers improve resilience	Feedback Loop
Supply Chain Flexibility	Ability of the supply chain to adapt to changes	Index (0-1)	Flexibility enhances responsiveness	Causal Loop

	in demand or supply			
Supplier Diversification	Number of suppliers to reduce dependency on a single source	Count of suppliers	Higher diversity increases resilience	Stock-Flow Delays +
Information Flow Efficiency	Speed and accuracy of information exchange across the supply chain	Index (0-1)	Better information flow improves decision-making	Feedback Loop

The table lists vital definitional constraints of the operational variables of the Supply chain resilience configuration. Definitional variables of the constraints of the configuration system operational variables include lead time, size of the buffer inventory, flexibility of supply chain, diversification of suppliers, and the efficiency of the information flow. The various definitional variables constraints of configuration systems operational variables definitional used model, and system dynamism. This usually consists of feedback loops and stock and flow systems that model the core supply chain system's behavior on integrated flexibility of configurations.

Table 2: System Dynamics Model Parameters and Equations

Model Parameter	Description	Equation	Units	Example Values
Demand Fluctuation	Variability in demand for products in the supply chain	$D(t) = D_0 + \alpha * \sin(\beta * t)$	Units	$D_0 = 100, \alpha = 20, \beta = 0.1$
Lead Time	Time taken for products to move across the supply chain	$LT(t) = LT_0 + \gamma * (t)$	Days	$LT_0 = 5$
Supply Chain Flexibility	Ability to adjust to demand or supply fluctuations	$SF(t) = SF_0 + \delta * Demand Variance(t)$	Index (0-1)	$SF_0 = 0.8$
Inventory Buffer Size	Buffer size to absorb fluctuations in demand and supply	$IB(t) = IB_0 + \mu * D(t)$	Units	$IB_0 = 500$
Supplier Diversification	Degree of diversification in supply sources	$SD(t) = 1 / (1 + e^{(-\alpha * (t - T_0))})$	Index (0-1)	$\alpha = 2, T_0 = 3$

The following table specifies the major components, variables, and equations constructed within the model to predict the behavior of the complete supply chain. Demand variability within the model is expressed as a sinusoidal function that approximates constantly changing demand spikes. The functions of time represent lead time, while supply chain adaptability is determined by the variability of demand. The inventory buffer increases and decreases with demand, while the supplier diversification is modeled by a logistic function. These equations allow us to predict the dynamic interaction of configurable supply chain resilience. Some of these equations allow us to calculate the variables as the model progresses.

Table 3: Simulation Results for Different Resilience Configurations

Configuration	Lead Time (Days)	Inventory Buffer Size (Units)	Supply Chain Flexibility (Index)	Supplier Diversification (Index)	Operational Performance (Efficiency)
High Resilience	5	800	0.9	0.8	0.95
Moderate Resilience	10	600	0.75	0.6	0.85
Low Resilience	15	400	0.5	0.4	0.6
Flexibility-Focused	8	700	0.85	0.5	0.9
Diversification-Focused	12	500	0.7	0.9	0.88

This table displays the simulation results of operational performance (efficiency) achieved for different configurational values of lead time, inventory buffer size, supply chain flexibility, and supplier diversification in the supply chain resilience. Configurations with high resilience traits, low lead time, more flexibility, and superior supplier diversification yield better operational performance (95%). On the contrary, configurations with low resilience, high lead time, and lower buffer size show much less efficiency (60%). This table describes the influence of different resilience strategies on the efficiency of the supply chain in different operational configurations.

2. Conclusion

The focus of this study was the use of system dynamics simulation to examine configurations of supply chain resilience capabilities—redundancy, flexibility, agility, and collaboration. The findings depict the best operational performance in the presence of cost, service level, and recovery time. This was achieved by not maximizing any particular capability, but by achieving certain synergistic configurations instead. It was determined that reliance on redundancy, although stabilizing, imposed heavy cost penalties, which, in the long run,

adversely affected competitiveness. On the other hand, balanced investment in agility and collaboration unlocked superior resilience in all the various disruption scenarios. This validated the assertion of resilience as an emergent property of a system that is complex and adaptive system, where prediction through siloed analysis is impossible as a result of interplaying capability interactions producing unusual outcomes. From a practical perspective, the study is an important strategic pointer on the need to embrace a portfolio approach when building resilience that focuses on the adaptive capabilities as opposed to static buffers. Rather than merely high inventory stockpiling, managers must enhance agility by investing in real-time data analytics and enabling joint problem solving and risk sharing through deeper collaborative partnerships. The system dynamics model of this study will enable practitioners to predict the outcomes of their input and resource allocation choices by simulating various scenarios.

The model underscores the need to shift from reactive redundancy to proactive adaptability, even though the model provides a broad overview. There is the potential for future research to confirm the configurations in particular industrial settings and to analyze the impact of digital technologies on the facilitation of agility and collaboration on a broad front. In the end, the research demonstrates the need to build supply chains that are not only strong but also defensively and strategically resilient in the scope of the global marketplace to a configured, integrated set of capabilities.

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